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TEXAS INSTRUMENTS
INCORPORATED

SCIENCE SERVICES DIVISION

14 March 1967

Air Force Technical Applications Center
VELA Seismological Center
Headquarters, USAF
Washington, D. C. 20333

Attention: Captain Carroll F. Lam

Subject: Third Quarterly Report Covering Period December 3, 1966, Through March 2, 1967

AFTAC Project No.:	VT/6707
Project Title:	Large Array Signal and Noise Analysis
ARPA Order No.:	599
Name of Contractor:	Texas Instruments Incorporated
Date of Contract:	16 May 1966
Amount of Contract:	$593, 673
Contract Number:	AF 33(657)-16678
Contract Expiration Date:	15 May 1967
Program Manager:	Frank H. Binder Area Code 214 FL 7-5411, Ext. 443

Gentlemen:

WORK PROGRESS:

Due to the late availability (February, 1967) of long-period data, a no-cost extension of the contract from May 15 to June 25 has been requested. Action is pending on this request.

During the third quarter the contract work statement was amended by adding:

STATEMENT #2 UNCLASSIFIED

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"Evaluate the seismic discrimination capabilities of the LASA by applying presently developed nuclear identification parameters. The identification capabilities of the LASA shall be compared with results obtained from applying these same techniques to data from small arrays and any advantages or disadvantages of using the larger array described."

A milestone, called LASA Identification Study in this report, has been added to cover this study. This milestone represents about one-fifth of the total contract effort. None of the original work has been deleted but the effort on some of the milestones has been reduced.

Progress against the milestones and an indication of the direction of effort in the future is as follows:

Formation of Library of Short-Period Noise and Signals

The short-period data library was completed during the third quarter. Data are of good quality and about 90 percent usable. The unusable data are usually spiked or dead traces.

Formation of Library of Long-Period Noise and Signals

As of March 2, three long-period tapes (two noise samples and one signal) have been converted into the TIAC format. This was done by a Texas Instruments reformatting program from a copy of LASA slow-mode tapes.

An additional four tapes have been received and 22 others have been requested. These tapes will be reformatted by Texas Instruments from LASA slow-mode tape copies made by Seismic Data Laboratory.

The three tapes reformatted to date are of fairly good quality. Generally, about five to ten of the 63 long-period traces are unusable.

PILOT STUDY OF SUBARRAY PROCESSING:

A pilot study was run using two subarrays (B1 and C2) and one noise sample to determine a favorable method of subarray processing. Based on the results of the pilot study, the following procedure was adopted:

- Noise traces are equalized on the basis of total noise power within each subarray
- Each subarray is processed through a multichannel filter system which was designed from a theoretical model of signal (disc, V = 11 km/sec to infinity) and noise (annulus, V = 2 to 6 km/sec)
- A power spectrum of seis 21 and the MCF output will be calculated
- An average power spectrum of seis 21 and MCF output will be calculated (averaged over all subarrays)
- Various spectral ratios will be calculated

The subarray processing will result in velocity limited traces at each subarray for use in large array wavenumber analysis and coherence studies. This routine processing of the LASA noise samples is now in progress and should be completed in a few weeks.

From an analysis of the spectra the following will be determined:

- The spatial noise power variability from subarray to subarray of both single seis and velocity limited traces
- If certain subarrays have a noise field which is consistently high or low and, if so, is there any plausible explanation
- The time variability of the noise power for both the single seis and the velocity limited traces
- The comparison of the theoretical MCF with a straight sum and optimum filtering techniques using measured noise. This will be done for a few examples only
- The analysis of peripheral information, such as the implications of the noise field based on MCF noise rejection and power spectra

A report on subarray processing covering the analysis listed above will be a portion of the Final Report.

EQUALIZATION ANALYSIS:

Intra-Subarray

Three approaches have been used in studying seismometer equalization problems:

- The first approach is to equalize power spectra of large signals using a minimum phase filter. One event has been studied in detail, and results were fairly good. However, the event had a possible second phase present shortly after the initial P-wave (probably PcP), which limited evaluation of the technique. Thus, a second event is being studied to provide a more definitive evaluation
- Another approach is to run the group coherence on a large signal. If the signal differences are assumed to be the result of the recording apparatus, the filters designed by the group coherence program are a measure of the sensor systems' differences. This has not been attempted as yet. It will be done using some of the data used in the first approach
- The third approach is to equalize on the basis of total noise power. A pilot study indicated that this technique was adequate for production processing and thus it is being used on all LASA data. A statistical analysis will be made on the set of equalization coefficients obtained. For example, to combat seismometer gain inequalities in multichannel filter synthesis, it is usually assumed that the seismometer gain is a uniformly distributed random variable and the correlation matrix is then appropriately modified. The accuracy of the set of equalization coefficients' fit to this model will be determined

Inter-Subarray

The purpose of this study is to determine the feasibility of developing average equalization filters for subarray outputs for various epicentral regions. An ensemble of events will be collected for a particular epicentral region and an average Levinson cross-equalization filter will be designed using the large

events in the ensemble. The average filter will then be applied to each event in the ensemble and outputs will be compared with those obtained from equalization on a single event basis. If the average filter appears adequate, a second region will be chosen to determine whether the average filter is sensitive to particular regions. This study is now under way but no results are as yet available.

SIGNAL SIMILARITY:

Short-Period Signals

Signal similarity will be measured by the correlation coefficient technique and by comparing signal power spectra.

For the correlation coefficient analysis, variations of subarray outputs, single seismometers within a subarray, and single seismometers between subarrays will be studied. For all cases the time-shifted sum will be used as the reference trace, and coefficients between it and the individual outputs will be obtained. The mean and variance of the coefficients for each event will be computed and related to signal degredation (defined as the amplitude of the time-shifted sum divided by the normalized sum of the amplitudes of individual traces). Finally, the variations will be studied as a function of subarray and of event location, and the improvement obtained by Levinson equalizing the data will be evaluated.

For the spectral analysis, the same types of variations will be studied but for a limited number of events. Also, an attempt will be made to relate spectral variations to correlation coefficient variations.

Data processing on short-period signal similarity is about 40 percent complete, but no results will be given at this time because the processing has to be completed before the data can be meaningfully interpreted.

Long-Period Signals

Recordings of about 12 signals from the 3-component, long-period array will be available for analysis. These recordings usually have P-, S-, and surface-wave arrivals. For those events which have a satisfactory signal-to-noise ratio, the following will be computed:

- The correlation coefficients for the P-wave on the vertical components. (If the P-wave is well recorded one or both of the horizontal components, correlation coefficients will also be obtained for them.)
- Correlation coefficients for the S-wave for all three sets of components
- For the surface wave, correlation coefficients for at least those stations which are approximately equidistant from the event's epicenter

In addition, signal degredation resulting from both a straight sum and time-shifted sum will be studied for all three types of arrivals, and brief analysis of moveout anomalies will be undertaken.

NONTIME STATIONARY SIGNAL EXTRACTION:

The problem of optimum signal extraction, when the first part of the data is noise and the time aligned signals are present in the last part of the data, has been separated into two phases for computational purposes. First, the noise in the signal is estimated from the pure noise and subtracted from the observed signal plus noise. Then optimum signal extraction filters are designed to apply to the signal plus noise error. The series of programs to evaluate this procedure is now being developed.

The programs necessary to perform the first computational task are now complete. The first program uses the covariance matrix of the noise to design prediction filters iteratively. The program contains an option to plot the percentage of predictability against the number of points being predicted ahead for each channel. These plots can be used in evaluating the general predictability of the noise. The second program computes the covariance matrix of the noise prediction error for use in the second phase computations. Finally, a program has been written to apply the prediction filters and to plot the prediction error.

The programs necessary to perform the second computational phase have been written and are currently being debugged and tested. The major program in this phase designs signal extraction filters (X) which satisfy the general system of equations

$$(S + N')X = S$$

where

S is the covariance matrix of the signal model, and

N' is the covariance matrix of prediction error.

Since S + N is not Toeplitz in form, a general matrix inversion will replace the Levinson iteration. The application program is also being extended to include application of the filters to the signal plus noise error in order to obtain the optimum signal.

While the final programs are being completed, evaluation of the series is being planned and implemented. As the first step in this evaluation, 25-point filters have been designed to predict 15 points ahead using a sample of noise data. Initial results appear promising but no conclusions concerning the effectiveness of the procedure can be drawn until all programs are complete.

In addition to the evaluation of the nontime stationary versus stationary processing, some incidental information on the predictability of seismic noise will be obtained. Here predictability is prediction many points ahead in time, using an array of seismometers to predict each individual seismometer.

RESOLUTION OF EVENTS:

The two events now being used in the resolution of events study are from Turkey ($\Delta = 83.6^{\circ}$, $Az = 35.7^{\circ}$) and Algeria ($\Delta = 86.2^{\circ}$, $Az = 58.6^{\circ}$). Distance between the epicenters of the two events is about 1700 miles. The events were time-shifted so that the Algerian event had infinite apparent horizontal velocity and the Turkey event had 55 km/sec horizontal velocity. Shifting preserved their actual wavenumber separation and allowed time-domain filter design since time delays between the subarrays were reduced. Moveout anomalies were compensated for and each channel was equalized on the basis of total energy over the signal gate. The two events were then composited so that they overlapped in time.

Since the Turkey and Algerian events were chosen, several additional pairs have become available. At least one more pair will be studied in detail.

The pair will be chosen to have high signal-to-ambient noise ratios, about the same total energy, about the same frequency content, and closer epicenters than the Turkey-Algerian pair.

Three filter systems have been designed: a straight sum, an infinite velocity multichannel filter, and a signal extraction multichannel filter (i.e., an MCF which calls one event signal and the second event noise). Thirteen channels (A-, C-, E-, and F-ring subarray outputs) were used in all cases, partly because of convenience in processing and partly because the spectral window does not change much when the B-ring is added. These filters are now being evaluated, and indications are that excellent separation of the events will be obtained.

Study of Mantle P-Wave Noise

Work is proceeding which will try to do the following:

- Determine the spatial coherence of the mantle P-wave noise
- Determine the spatial organization and generators of the high velocity noise. Also, determine the portion of the total noise field which is mantle P-wave noise
- Determine the time variations in the P-wave noise
- Detect and characterize any discreet wavelets in the high velocity noise field

Coherence between subarray outputs has been indicated to be very poor. The 2-channel coherence between the straight sum output of two subarrays approximately 10 km apart is essentially zero except right at the microseism peak ($f \approx 0.3$ cps). This lack of coherence is being checked by determining the group coherence between the two subarrays. This is a linear combination determined so that the outputs have maximum coherence.

An accurate estimation of the group coherence is dependent upon sufficient data. To get an estimate of the statistical reliability of such an estimate, two groups of 19 channels of random noise, 4096 points each, were processed as two subarrays. The coherence of these two "subarrays" averaged about 0.64. Experiments are under way to determine the number of channels and data length which will give an acceptable reliability to the estimate

of the group coherence. Results to date indicate that using ten channels in each subarray will give reasonable results with the data length available (two or three adjoining 8-minute segments).

The multichannel predictability of subarray filtered outputs is also being investigated. The prediction error as a function of frequency will be calculated for many different subarray configurations. This can be done efficiently using the multiple coherence program developed under this contract. The results will be compared with the multichannel predictability of several reasonable noise models.

The spatial organization of the P-wave noise will be studied using conventional wavenumber spectra from the large array and K-line spectra from three of the small arrays. The large array gives good resolution but has a complicated spectral window. The K-line spectra have fairly good resolution, and since the seismometers are regularly spaced, it is possible to integrate these spectra to obtain the energy in any velocity band. These K-line spectra will also give information about the lower velocity modes and an indication of the similarity of wavenumber spectra at fairly distant (200 km) sites.

The generating mechanisms of the P-wave energy will be identified and described insofar as possible. Any additional information about generators of the lower velocity modes will also be analyzed.

Experiments which try to recognize discreet P-waves arriving in the ambient noise have been unsuccessful to date. In general, the experiments have taken the Fisher statistic at several (4 or 5) of the closely spaced subarrays and examined it for correlated peaks. Experiments with synthetic examples have indicated that this processing has not been done in an optimum fashion. The noise will be processed again, based on the experience gained from synthetic examples.

In addition, a moving power spectral estimate will be run of the same data. The purpose will be to look for abnormally high (statistically speaking) power densities in certain frequency bands. This data will be correlated with highs in the Fisher statistic.

STUDY OF LONG-PERIOD NOISE AT THE MONTANA LASA:

As of December 2, two 80-minute long-period noise samples had been demultiplexed and briefly examined. Spectral analysis indicated that:

1) The long-period data can be resampled by five to a 1-sec sampling interval. This results in a folding frequency of 0.5 cps. Actually, the system has such a sharp cutoff on the high side that there is no appreciable seismic energy above about 0.25 cps.

2) The power spectra of the vertical components are quite similar over the array. This indicates that the verticals are well equalized among themselves.

3) The power spectra of the horizontal components are also quite similar. This indicates that the horizontals are well equalized among themselves.

4) The horizontal component spectra are generally similar in shape to but higher than the vertical components. However, there are no instrument calibrations yet available.

5) The RMS system noise appears to be 2 to 3 digital units.

A large amount of multichannel predictability information will be acquired using various combinations of sensors. These results will be presented as a function of frequency using the multiple coherence program. This processing has already begun on the two noise samples which are "in house."

Wavenumber analysis will be made of all three components for each noise sample. It is hoped that the generating mechanisms can be identified and described.

The plan is to obtain about 10 long-period noise samples recorded between November, 1966, and February, 1967. It is anticipated that about 75 percent of this data will be usable.

The lack of calibration data will make it impossible to compare power spectra taken on different days or to put units of ground motion on the spectra. It also makes it impossible to know whether the ambient noise is really much stronger on the horizontals or not. However, the absence of calibration data generally will not be much of a handicap to the long-period noise studies.

COMPARISON OF MAXIMUM LIKELIHOOD AND WIENER PROCESSING TECHNIQUES FOR SPECIFIC EVENTS:

Maximum likelihood and Wiener filtering have been compared previously on both a theoretical and an experimental basis.[1, 2] In addition, Flinn, Hartenberger, and McCowan[3] compared maximum likelihood processing with summation processing using LASA data. As a consequence, this analysis will be limited to comparing the performance of the Wiener filter being used for the subarray processing to the maximum likelihood filter results.[3]

The reformatted data obtained from SDL is in a format which makes it impossible to compare exactly with those previously obtained using maximum likelihood filters.

LASA IDENTIFICATION STUDY:

Data Acquisition

The requested data library for this study has been received from SDL and consists of 27 earthquakes and 12 underground explosions. Four regions

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[1] Kelley, E. J., and M. J. Levin, 1963: Signal Parameter Estimation for Seismometer Arrays, Lincoln Laboratory Report, 21 November.

[2] Jackson, D., 1965: A Comparison of Wiener and Maximum Likelihood Multichannel Filtering, Texas Instruments Summer Development Report, 25 October.

[3] Flinn, E. A., R. A. Hartenberger, and D. W. McCowan, 1966: Two Examples of Maximum Likelihood Filtering of LASA Seismograms, Teledyne Industries Report, 8 June.

are represented in the earthquake ensemble and two in the explosion ensemble. PDE information suggests ranges in event magnitude from 3.7 to 6.3, in focal depth from 0 to 650 km, and in epicentral distance from 39° to 104°. Where possible, observed magnitudes and focal depths (at LASA, using the band-limited large array beam-steer output) will be substituted for the PDE average values.

Event Preprocessing

All events have been demultiplexed, beam-steered at the subarray level, resampled 2:1, aligned according to theoretical large array time shifts, and filtered with a 0.8 to 2.8 cps bandpass filter. The center seismometer (10) from the B1 subarray has also been demultiplexed, resampled, and band-limited. (In certain cases, the B1 subarray was unusable and the A0-10 seis was substituted.)

Crosscorrelations have been computed between subarray outputs over the signal wavelet for each band-limited event. Time residuals (deviations from theoretical alignment) are being determined from these correlations. Studies of the time residuals and their relationship to other event statistics are underway. The crosscorrelations are also being used for the design of equalization filters for each event.

The design and application of equalization filters (equalizing all subarray outputs to the B1 subarray output) will be completed by March 10.

Comparisons are being made between eight output traces. These include the single seismometer (B1-10) data before and after band-limiting, the beam-steered, band-limited A0 subarray output, the large array beam-steer output before and after band-limiting, and the equalized large array output. Editing and plotting of these various output traces is virtually complete.

Evaluation

Measurements of peak signal-to-RMS noise have been completed for all edited traces. Computations of the discrimination parameters will be completed by March 10. The analysis of the parameters should be completed by March 17 and a special report on this task should be completed about March 23.

FINANCIAL STATUS:

The financial status of the contract through January 31, 1967, is summarized on the attached Cost Planning and Appraisal Chart.

Yours very truly,

TEXAS INSTRUMENTS INCORPORATED

Frank H Binder

Frank H. Binder
Program Manager

FHB:pr
Attach.

PROJECT NUMBER	CONTRACT NUMBER	PROGRAM DESCRIPTION
57060	AF 33(657)-16678	LASA Evaluation

COST PLANNING
& APPRAISAL CHART TI-10311

COLUMN CODE: 1. Monthly budget direct costs as projected in negotiated price.
2. Monthly actual direct cost
3. Cumulative budgeted direct dollars
4. Cumulative actual direct dollars
5. Variance budgeted vs. actual to date
6. New estimate of total direct costs to complete
7. Original estimate of total direct costs
8. Current estimate of direct costs

COST DATA

DIRECT COSTS

TASK/ITEM IDENTIFICATION	BUDGET EXPENSE MONTH: Jan. 1967 Budget 1	Actual 2	EXPENDITURES TO DATE Budget 3	Actual 4	BUDGET VAR. (+ OVER − UNDER) 5	NEW ESTIMATE TO COMPLETE 6	TOTAL ORIGI ESTIM 7
Contract not broken down by Tasks	40,000	37,149	192,185	185,220	-6,965	194,193	379,
SUB TOTAL	40,000	37,149	192,185	185,220	-6,965	194,193	379

INDIRECT COSTS

TASK/ITEM IDENTIFICATION	MONTH Jan. 1967	TO DATE	NEW ESTIMATE TO COMPLETE	TOTAL ESTIMATED INDIRECT COSTS ORIG. EST.	CURRENT EST.	VAR. (+) OVER (−) UNDER	CODE
	17,783	84,514	75,777	160,291	160,291	0	
SUB TOTAL	17,783	84,514	75,777	160,291	160,291		
G & A	1,684	7,849	12,120	19,969	19,969		
FEE	3,454	16,933	17,067	34,000	34,000		
TOTAL ESTIMATED COST AND FEE	60,070	294,516	299,157	593,673	593,673	0	

1

uation

DATE 7 March 1967

ctual to date
rect costs to complete
l direct costs
t costs

9. Variance budget vs. new estimate
10. See instructions

NEW ESTIMATE COMPLETE	TOTAL ESTIMATED DIRECT EXPENDITURES			% COMPL. TOWARD TECHNICAL OBJECTIVE
	ORIGINAL ESTIMATE	CURRENT ESTIMATE	VARIANCE (+) OVER (—) UNDER	
6	7	8	9	10
94, 193	379, 413	379, 413	-	
94, 193	379, 413	379, 413	-	45

SCHEDULE DATA

SYMBOL CODE: Start event (scheduled) Complete event (scheduled) Anticipated slippage Actual slippage Milestone

TIME: WEEKS MONTHS

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26

COSTS R. (+) OVER R. (—) UNDER	CODE	ANALYSIS OF SIGNIFICANT PROJECT VARIANCES & PROBLEMS (COST - SCHEDULE - PERFORMANCE)
0		Work is behind schedule because of unavailability of long-period data. A no cost time extension has been requested.
0		

2